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Final Report



INVESTIGATION AND EVALUATION OF METHODS FOR
PULSE RISE-TIME MEASUREMENT

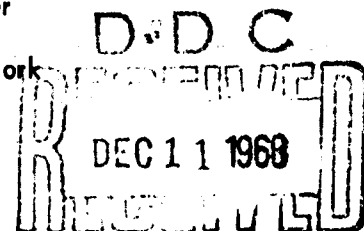
Paul Hudson
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National Bureau of Standards
Radio Standards Laboratory

TECHNICAL REPORT NO. RADC-TR- 68-207
October 1968

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York



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FOREWORD

This final technical report was prepared by National Bureau of Standards, Radio Standards Laboratory, Boulder, Colorado under Contract No. F30602-67-C-0163, Project 4540, Task 454001, covering the period January 1967 to February 1968. The RADC project engineer was Lt. James W. Hayes, EMCVM-1.


Thanks are given to Dr. Norris S. Nahman for his many helpful suggestions during the course of this work and to Mrs. Betty I. Klundt for her efficient preparation of the report.

This technical report has been reviewed and is approved.

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ABSTRACT

This report presents the results of an investigation into various methods for measurement of the rise time of very fast pulses. The methods pursued under the study were: (1) the investigation of various types of coaxial deflection structures for use in a real-time oscilloscope, (2) characterization of the response of sampling oscilloscopes in the frequency domain and calculation of the response in the time domain and (3) the determination of pulse shape by the Gaddy autocorrelation technique. The techniques can be used to characterize the voltage waveform $V(t)$ of fast pulse systems such as impulse generators, time domain reflectometers and some digital and radar systems.

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EVALUATION

This effort was a preliminary investigation to determine the best methods for the measurement of sub-nanosecond pulse rise times. The application of immediate interest is for the precise calibration of the output voltage vs time waveform of impulse generators, which are used as internal calibrators in RFI meters. The eventual goal of the program is the development of an impulse generator calibration standard and establishment of calibration services at both NBS and Air Force PMEL levels. An effort to accomplish this is programmed for FY-69. These services would also be of interest to those people concerned with the development of fast pulse radar, communications and digital systems.



JAMES W. HAYES
1st Lt, USAF
Effort Engineer

INTRODUCTION

This report discusses the results of an investigation into various methods for measurement of the rise-time parameter of baseband pulses and step-functions. Knowledge of the rise-time is necessary in order that the waveform $V(t)$ can be completely characterized. Fast-rise pulses are used extensively for modulating RF carriers in communications systems, telemetry, and the newer radar systems. They also have a variety of uses in electronic computers and test systems such as time-domain reflectometry and impulse generators.

The methods considered included the following:

(1) Investigate various types of coaxial deflection structures for use in a real-time oscilloscope.

(2) Measure the amplitude and phase response of one or more sampling oscilloscopes in the frequency domain and calculate the response in the time-domain.

(3) Investigate a special pulsed electron-beam sampling system.

(4) Investigate certain measurement techniques in the frequency domain suitable for correlation with measurements in the time-domain.

(5) Investigate a modified Gaddy technique.

Of these, (1), (2) and (5) appeared to offer promise of relatively quick results and hence were the ones pursued. The work on all three methods progressed beyond the investigation stage and well into the development stage.

The goal of NBS is to develop the capability to accurately measure state-of-the-art rise-times which at present is approximately 30 picoseconds. With two of the methods we were able to achieve measurement capability to 100 ps in 50 ohm coaxial system with uncertainties of the order of 2 percent to 3 percent. Each of the three methods is described in the following paragraphs.

I. PREDICTION OF THE FREQUENCY AND TRANSIENT RESPONSES OF THE BEAM DEFLECTION IN A SLOW TRAVELING WAVE OSCILLOSCOPE *

James R. Andrews

A. INTRODUCTION

A pulse measurement system consists of three basic parts (1) the pulse generator, (2) the interconnecting transmission line networks, and (3) the detector. To date the most useful instrument for pulse detection has been the oscilloscope. For extremely fast pulse observations in the sub-nanosecond ($< 10^{-9}$) region there are (at present) two types of oscilloscopes; the sampling oscilloscope for repetitive waveforms and the direct deflection oscilloscope for single transients. This proposal is mainly concerned with the study of a particular direct deflection type of oscilloscope, the traveling wave cathode ray tube (TWCRT). The detector parameter that will be of major interest is the inherent voltage transition time (rise-time) of the TWCRT vertical deflection.

In principle, the transition time can be determined by applying a voltage step function at the vertical deflection input terminals of the TWCRT, and with a suitable time base applied (horizontal deflection), observing the resultant trace. In practice this is not entirely feasible due to the non-zero transition time of the pulse generator and distortions encountered in the connector-transmission line network.

The reason for wanting to predict the TWCRT response is related to the desire to be able to completely characterize the response of an entire pulse measurement system. Thus, if a relatively simple structure is used for the TWCRT that can be mathematically analyzed,

* A PhD dissertation proposal by James R. Andrews to Graduate School, University of Kansas.

one unknown of the system is removed. This will be a bootstrap process; it will be necessary to consider other aspects of the rest of the system [1], as it will be impossible to experimentally verify the TWCRT response without considering the other parts of the system.

B. SYSTEM CONSIDERATIONS

Pulse Measurement Systems. Typical systems are shown in figures 1 and 2. In figure 1 the signal delay line is necessary because the time base must be triggered by the transition itself to enable the horizontal sweep to start moving before the signal arrives at the vertical deflection plates of the CRT. Thus, the pulse transmission line network must be considered as a 3-port network. A signal delay line is not necessary if it is possible to trigger the pulse generator, figure 2.

Dispersive Elements. No generator can generate a perfect step. Likewise, no transmission line will faithfully transmit a step without distortion. Normal transmission lines degrade pulses usually because of skin effect [2] while at low temperatures, the anomalous skin effect predominates [3]. Even the use of superconductive transmission lines is not a cure all as effects similar to the anomalous skin effect are present [4]. Other effects [3] to be considered in transmission lines are dielectrics, internal reflection, radiation, coated conductors, periodic loading, and higher order modes.

Another very important factor is the coaxial connector problem. Much progress has been made in the last ten years to improve RF connectors [5]. Even some of the better connectors have been found to have higher order mode resonances [6] in the frequency range of interest in very high speed pulse investigations. The effect of multiple reflections from connectors and from the various characteristic impedances of the different parts of the system will also have to be considered.

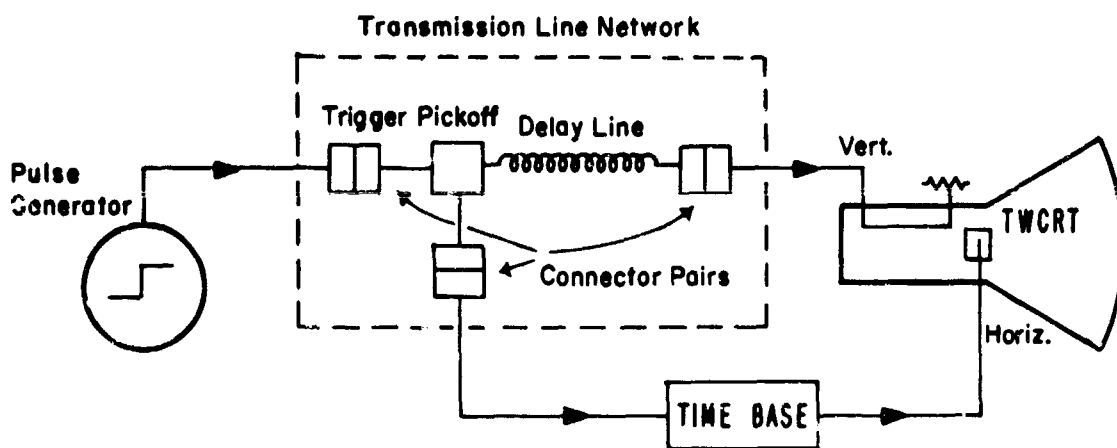


FIG.1 TYPICAL DELAY LINE PULSE MEASUREMENT SYSTEM

Auxiliary Pulse Generator
With Variable Advance-Delay
Trigger Generator

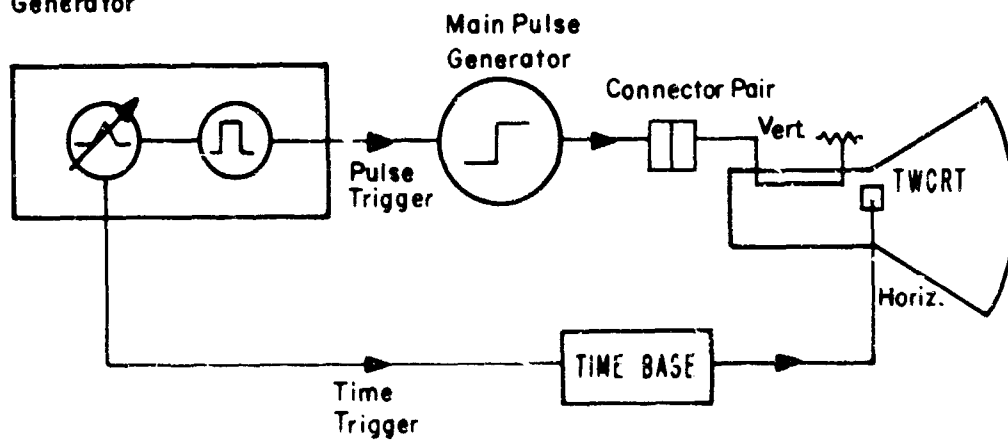


FIG.2 TYPICAL PULSE MEASUREMENT SYSTEM WITH AUXILIARY TRIGGER GENERATION

System Analysis. Individual portions of the system may be considered in terms of their transfer function and characteristic impedance. But, to account for interaction between various components connected in cascade, it will be necessary to use a matrix description of each component. Possible matrices to be considered are the ABCD matrix, the scattering (S) matrix, and the transformation (T) matrix [7].

C. PROPOSAL

Slow Wave Structure Analysis. It is proposed that a slow traveling wave deflection structure be analyzed for use in a direct deflection oscilloscope. Oscilloscopes have been built with this type of structure [8-19], but to the author's knowledge no detailed analyses of the respective deflection structures have been made. A possible slow wave structure to be studied is the transversely slotted strip line, figure 3. In this structure the signal wave will propagate in a slow wave mode at the same velocity and in the same direction as the electron beam, thus increasing the deflection sensitivity and the bandwidth.

There appear to be two alternative means of analysis for determining the step response of the structure. The first is a boundary value solution of the electromagnetic fields. The second method would analyze the structure as an alternating series of two types of transmission lines periodically loaded with fringing capacitances, figure 4. Either method would be analyzed in the frequency domain. The fringing capacitance may be found experimentally using Whinnery and Jamieson's technique [20] of constructing a simple resonator with a single abrupt step in the characteristic impedance, figure 5.

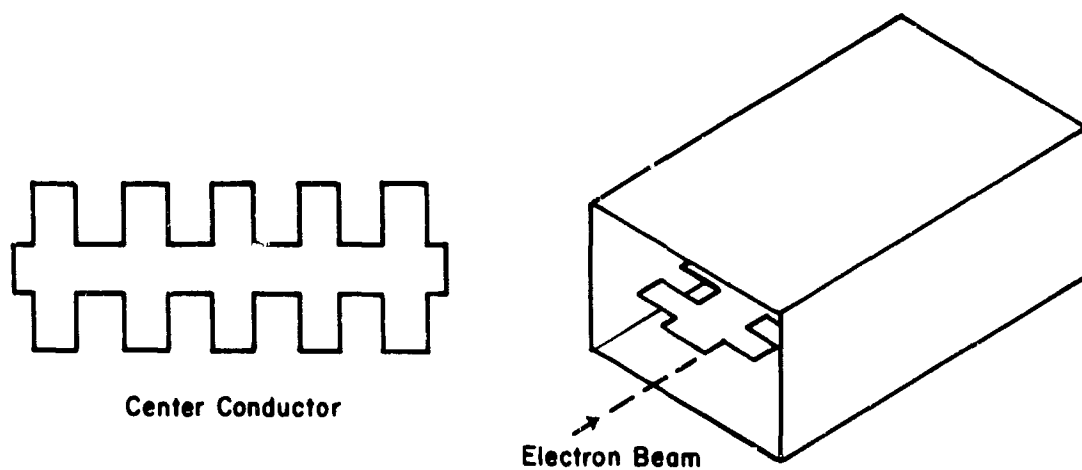


FIG. 3 TRANSVERSELY - SLOTTED, STRIP LINE, SLOW TRAVELING WAVE CRT DEFLECTION STRUCTURE

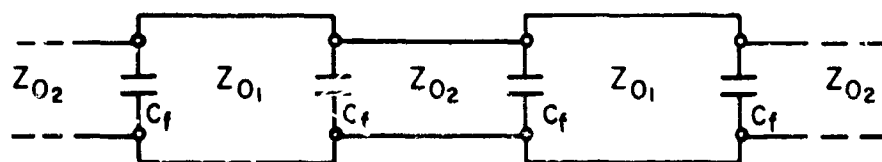


FIG. 4 TRANSMISSION LINE EQUIVALENT CIRCUIT OF FIG. 3

Beam Deflection Analysis. Once the fields are known within the deflection structure it will be possible to analyze the beam deflection. Lewis and Wells [21] give sample calculations for beam deflection from ordinary parallel plate deflectors. Stonebraker [22] has made a rigorous analysis of a simple traveling wave parallel plate deflection system in which the signal wave travels in the same direction as the electron beam but at a higher velocity. His analysis was done in the frequency domain. Work done on this dissertation to date has included library research and an independent derivation of Stonebraker's results by a time domain analysis.

Experimental Work. It is also proposed that experimental instrumentation be designed and built to provide correlation between experiment and theory. In terms of theory, this will involve an analysis of the entire system as mentioned earlier. For the experimental work, a cathode ray tube (CRT) with a demountable vacuum system is available [8] in which various deflection structures may be tested. Also, a time domain reflectometry [23, 24] system (TDR) is available to check for impedance discontinuities in the deflection structure although mechanical scaling [25] in size will no doubt be necessary. The frequency response of the deflection structure will be investigated by the usual direct methods if possible. Another technique to be investigated is that shown in figure 5. In this one, the amount of signal coupled to the electron beam is sampled by the RF probe inserted in the vertical E field. Either a radio receiver or synchronous detection will be used. This method should have the advantage of extreme sensitivity and accuracy.

In line with the experimental work, a Lee Microscilloscope was obtained from the Atomic Energy Commission (indefinite loan). This is a large, self-contained instrument except for the sweep voltage which

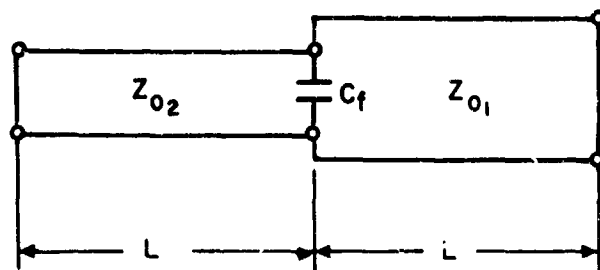


FIG. 5 RESONATOR CIRCUIT TO MEASURE C_f

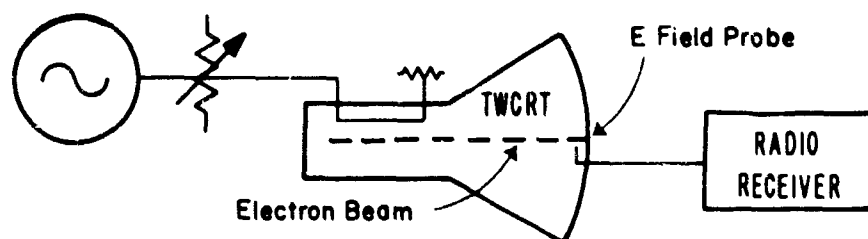


FIG. 6 ALTERNATE METHOD TO MEASURE FREQUENCY RESPONSE

must be applied from an external source. A particularly attractive feature is the demountable deflection structure which will allow us to use a structure of our own design.

The vacuum system on the instrument was fitted with new, more efficient pumps and a ramp generator for driving the deflection plates has been designed.

Even though this contract has terminated, we plan to continue work on the real-time oscilloscope at whatever levels are allowed by future funding.

II. PREDICTION OF THE RISE-TIME OF A SAMPLING OSCILLOSCOPE FROM MEASUREMENTS IN THE FREQUENCY DOMAIN

Paul A. Hudson, William J. Blank

The rise-time of an oscilloscope may be defined as the observed time of rise of the display (10 percent to 90 percent of maximum amplitude) when an ideal step-function is applied to the input. Generation of ideal step-functions is, of course, not possible with any real system. It is possible, however, to estimate from geometrical and electrical considerations of a generating system, the rise-time of physically realizable functions [26]. When a step-function (or pulse) of finite, known, rise-time is used to measure the rise-time, of an oscilloscope, the actual rise-time, t_r , is given by

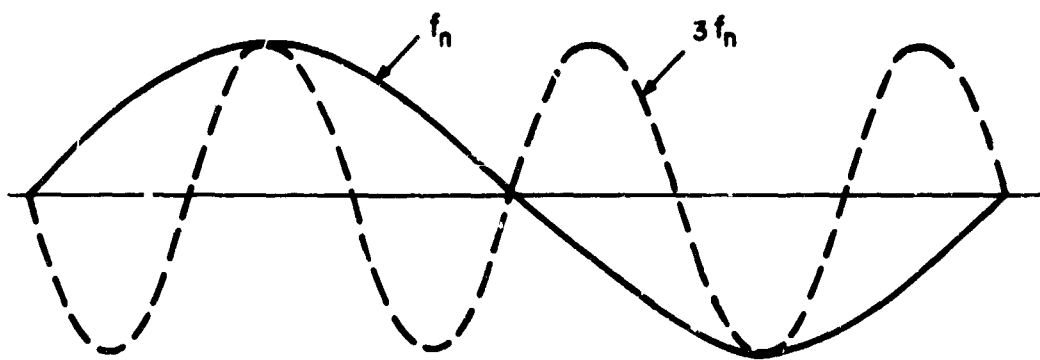
$$t_r = \sqrt{t_{\text{obs}}^2 - t_{rp}^2} \quad (1)$$

where t_{obs} is the observed rise-time and t_{rp} is the step-function rise-time. This equation is exact only when the oscilloscope response is Gaussian. When t_{obs} and t_{rp} are of the same order of magnitude, the accuracy in measuring t_r by this method is no better than the accuracy with which t_{rp} is known. For state-of-the-art rise-times (≈ 20 ps), the uncertainty in t_{rp} may be as large as 20 percent to 30 percent.

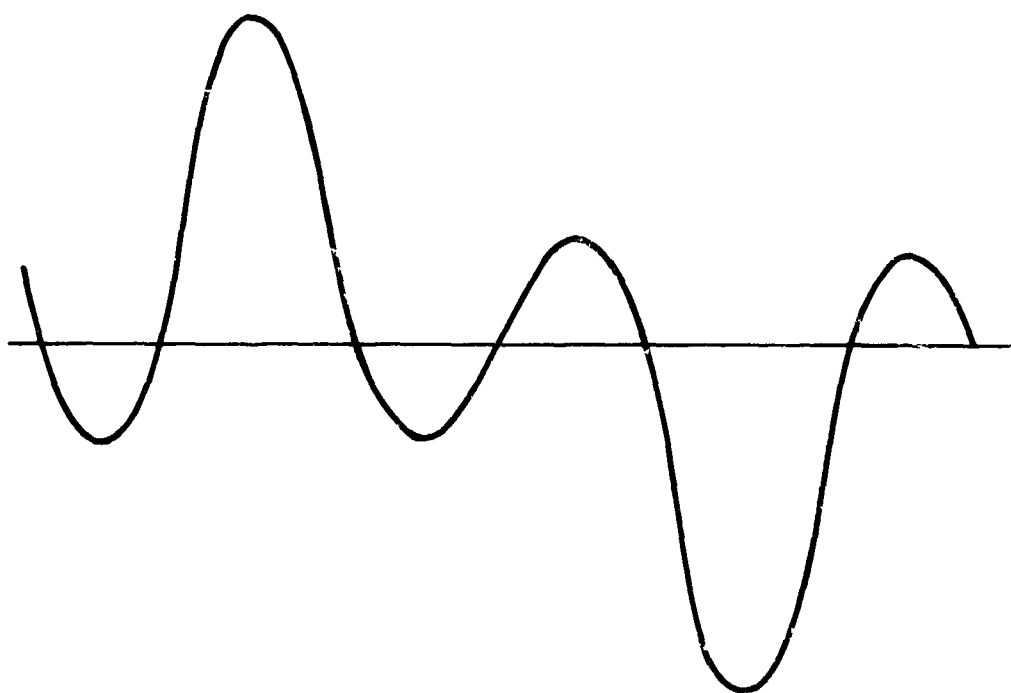
Such large uncertainties are beyond the limit that we would like to achieve. It was for this reason and also to provide a method independent of pulse parameters, that it was decided to calibrate the sampling oscilloscope in the frequency domain.

Complete calibration or characterization of the oscilloscope in the frequency domain required that both its amplitude and phase response versus frequency be measured. The amplitude response is relatively simple to measure by using calibrated RF voltage and/or power bridges. Measurement of the phase response characteristics is more difficult because oscilloscopes are not simple four-port devices. They have an electrical input but a visual output presentation. For this reason, conventional phase-measuring methods could not be used and a special technique had to be developed. The technique involves the application of a signal of frequency, f_n , and its third harmonic, $3f_n$ (coherent with f_n), to the input of the oscilloscope sampling head. The theory of the technique is based on the fact that, if the phase relationship of the two signals at the input is known, then the phase dispersion due to oscilloscope can be determined by simply observing the phase relationship in the visual output. The phase relationship between the two signals is adjusted as shown in figure 7a so as to yield the sum shown in figure 7b. The detector, used to determine when the positive-going half-cycles of the two waves were coincident in time, was a back-biased, hot carrier diode in a coaxial, feed-thru mount. The mount was connected to the input of the scope sampling head. A block diagram and a photograph of the equipment arrangement is shown in figure 8 and figure 9, respectively.

The relative phase of one of the signals was then adjusted to produce a maximum indication from the diode detector. The position of the trombone phase-shifter, to the nearest 0.001°, was recorded. Next, the phase-shifter was adjusted to produce a maximum on the oscilloscope



a. Phase Relationship Between f_n and $3f_n$ at Oscilloscope Input



b. Sum of $f_n + 3f_n$

Figure 7

display and the position of the indicator again recorded. The difference in the two positions of the phase-shifter was converted to degrees and recorded as the phase-shift for the measurement. Several measurements were made at each f_n so as to keep the measurements in statistical control. Due to its broadness, the exact position of the voltage peak was difficult to locate. Thus, the random uncertainty in the measurements accounted for the largest part of the total uncertainty estimated to be 1.5 degrees. Measurements were made at the following f_n and $3f_n$ frequencies.

f_n MHz	$3f_n$ MHz
30	90
50	150
100	300
333.3	1000
400	1200
1000	3000
1333	4000
1666	5000

Up to 4000 MHz there appeared to be no phase dispersion in the oscilloscope within the limits of uncertainty of the measurements. Because of the results obtained at the higher frequencies, it was assumed that no dispersion would exist below 30 MHz and no measurements were made below this frequency.

It was found that the back-biased diode detector was not usable above 4000 MHz because of a resonance effect near 5000 MHz. Thus, anomalous phase effects were obtained at the 1666 - 5000 MHz point and no meaningful measurements could be made. A new diode mount has been constructed but we have not made any additional measurements.

EQUIPMENT ARRANGEMENT FOR MEASURING THE PHASE RESPONSE OF A SAMPLING OSCILLOSCOPE

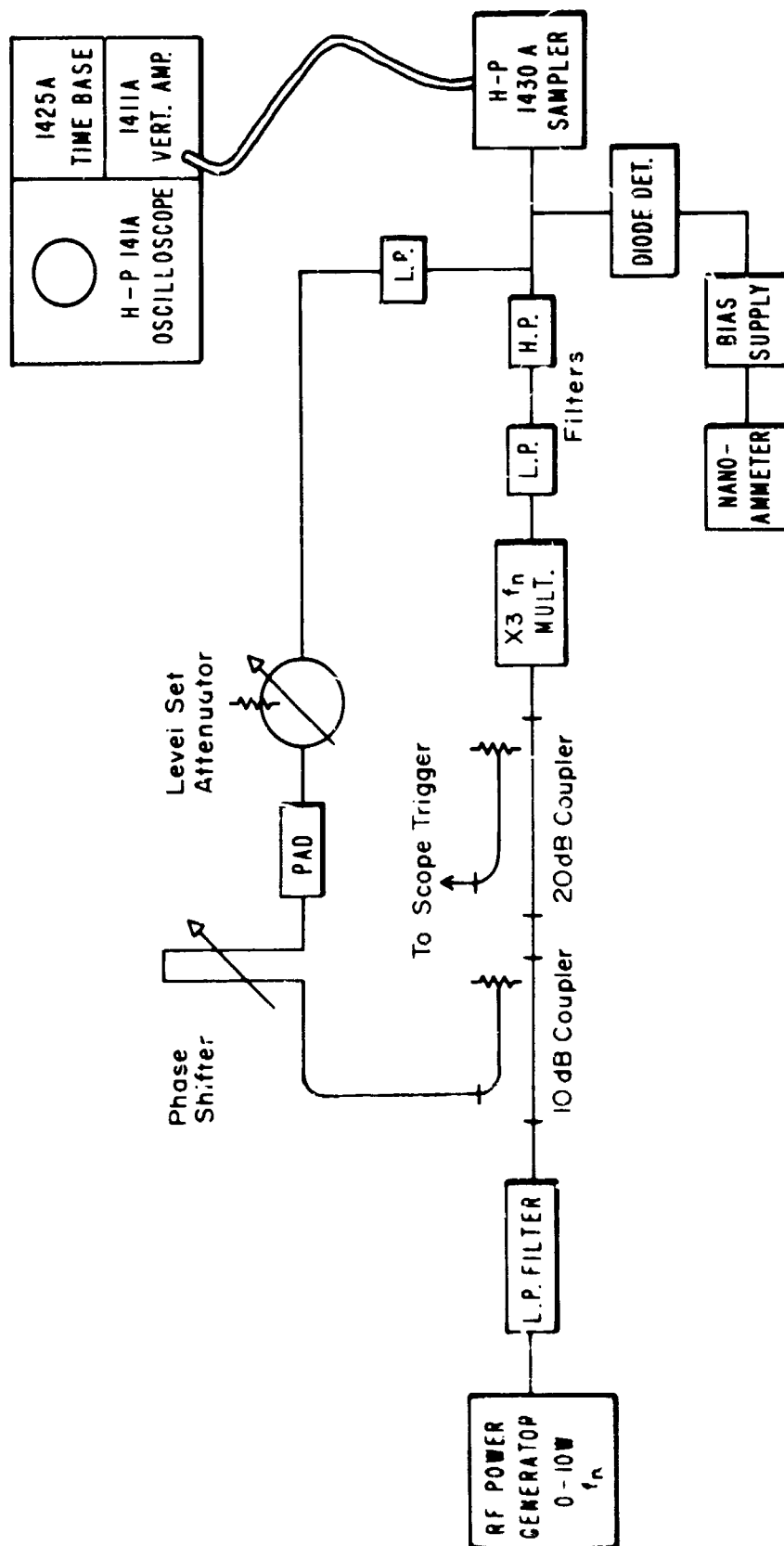


Figure 8

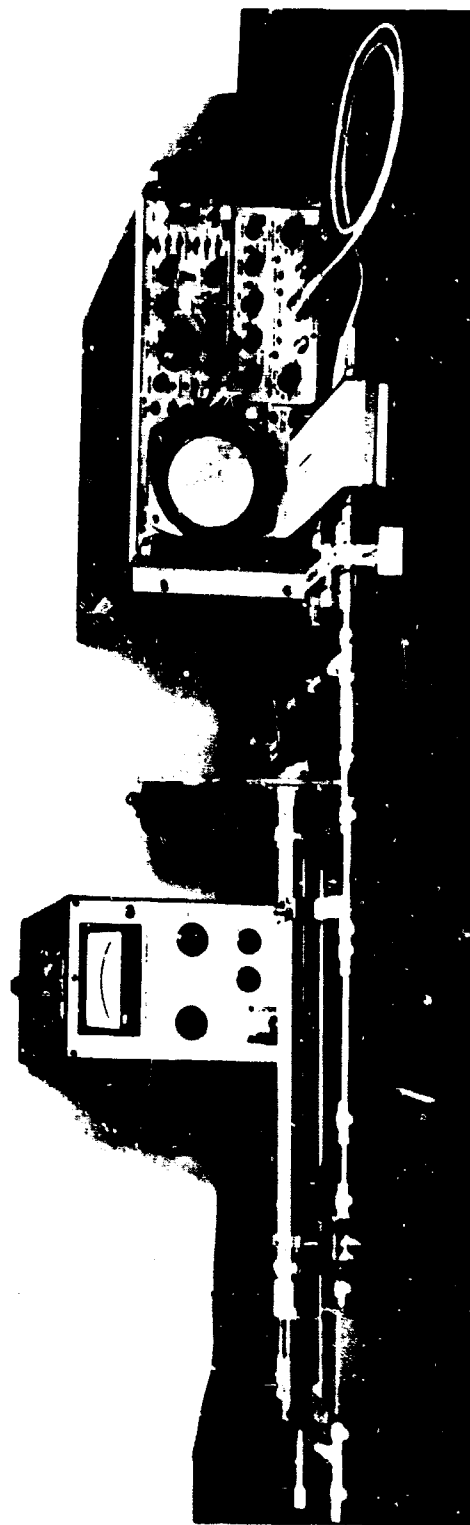


Fig. 9 Photograph of equipment arrangement for measuring the
phase response of a sampling oscilloscope

With the new mount and a new measurement sequence, resonance effects will not perturb the measurements in the same manner, and we hope to continue to 10 GHz and beyond.

In the frequency band where no phase dispersion was observed, we can calculate the equivalent rise-time or step-response by use of the approximate, empirical equation [27]

$$t_r = \frac{0.35}{f(\text{GHz})} \text{ ns} , \quad (2)$$

where f is the frequency at which the response is down 3 dB. Derivation of this equation is based on the assumption that the circuit is a simple RC network. For Gaussian circuits, the equation is [28]

$$t_r = \frac{0.45}{f(\text{GHz})} . \quad (3)$$

Thus, since the amplitude response was essentially flat (± 3 percent) and the phase response was linear ($\pm 1.5^\circ$) to at least 4 GHz, the rise-time, t_r , is no greater than $0.35/4 = 0.09$ ns.

The oscilloscope is useful in its present state of calibration to measure the rise-time of pulses slower than about 0.1 ns. It would be adequate, for example, to measure rise-times in the 0.3 ns range where, at present, a military requirement exists. Assuming that the actual rise-time of the oscilloscope is 0.05 ns, it will be shown that taking the rise-time as 0.09 ns causes only a small error in the calculations. Referring to (1) and assuming an observed rise-time of 0.35 ns, we compute

$$t_{r_1} = \sqrt{(0.35)^2 - (0.09)^2} \approx 0.34 \text{ ns} ,$$

and

$$t_{r_2} = \sqrt{(0.35)^2 - (0.05)^2} \approx 0.35 \text{ ns} .$$

The difference is less than 3 percent for this case. When the observed rise-time is 0.2 ns, the difference increases to 12 percent.

In the frequency range where the amplitude response is not flat and/or phase dispersion occurs, the time-domain response will be calculated from the inverse Fourier transform equation

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{H(j\omega)}{j\omega} d\omega \quad (4)$$

where

$$H(j\omega) = \frac{1}{(\omega + S_0)(\omega + S_2)}$$

The complexity of this equation requires the use of a computer for solution.

III. DETERMINATION OF PULSE SHAPE BY THE GADDY TECHNIQUE

Arthur R. Ondrejka

A scheme for estimating pulse shape was described by Gaddy [29] in 1960. The basis for operation of this scheme is that if a pulse is passing through a transmission line in one direction and encounters an identically shaped pulse traveling in the opposite direction, a kind of standing wave is produced. Gaddy suggested analyzing the pulse shape by measuring the rectified average voltage at various points in this pseudo standing wave. His technique involved dividing the pulse into two equal parts with a coaxial tee and then recombining the parts at a detector. The standing pattern could be shifted by changing the delay in one of the paths.

A similar pattern is produced if the pulse is reflected from a short terminating a slotted line. The detector is moved through the voltage pattern as in an ordinary slotted line. However, a modified probe must be used for broadband coupling. The response of the probe should extend from dc to several GHz.

If the pulse has a voltage shape, $V(t)$, an equation for the output of the analyzer can be written. The form of the equation is a function of the kind of detector used. Several types have been considered, namely, a linear diode, a square law diode, a peak reading diode [30], and a power detector. A voltage divider probe has also been built to view the voltage on a scope. The first two were used in Gaddy's original paper and again by Honnold [31]. The work described in this report deals with all of these detectors. The power detector is a micro calorimeter which can have greater predictable frequency response than the diode. The power detector equation is given as an example, since it is the least complicated.

If the time that the incident pulse reaches the detector is chosen to be zero, the time of arrival of the reflected pulse is called τ . The power is measured as a function of this delay time $P(\tau)$, and is given by the following equation, where T is the repetition period.

$$P(\tau) = \frac{K}{T} \int_{t=0}^T \left(V(t) - V(t-\tau) \right)^2 dt. \quad (5)$$

Notice that this is a definite integral and after evaluation, the constant limits of integration replace the variable t . The power is then a function of only the delay τ rather than of time t . The power cannot be differentiated with respect to time to obtain the original $V(t)$. Thus, the process is irreversible. Some information can be obtained by differentiating the power with respect to the delay time τ and this is, in fact, done.

The prototype device developed on this contract, operates successfully with diodes but has not been used with a power detector. It is a modified slotted line made of precision 7 mm coax with a precision type N input connector. A coaxial short circuit is built into one end of the transmission line. The pulse enters the line, is reflected at the short, and must be absorbed in the $50\ \Omega$ source impedance. (See figure 10)

The probe enters the line through a slot just as in an ordinary slotted line. (See figure 11) The diode touches the center conductor, rectifies and squares the signal current (for square law diode operation), and passes it into an output cable. This short length of flexible coax is only 7/64 inch in diameter and appears as a loop in the photograph (figure 12). The probe tip must ride smoothly on the center conductor with a constant force. Any stiff cable connected to the probe will cause it to bind. The cable is terminated in a type N connector with the proper tapered section to maintain $50\ \Omega$. The proper output circuitry is connected at this point. The output is a dc voltage which is recorded as a function of location of the probe.

The probe position is adjusted with a precision ratchet which moves the probe in one half-inch increments. The vernier is a micrometer screw with a resolution on the order of 0.001 inch. This displacement is converted to delay time τ . Since the derivative of this data is needed, we recommend that a future probe be constructed using two diodes measuring the difference voltage between two closely spaced points in the line. Measuring the differential voltage would be more accurate than subtracting a small difference between two large numbers. This data of differential voltage (or power) versus delay time approximates the real pulse in only a gross way. The data can be greatly refined using even a simple computer.

BLOCK DIAGRAM OF MODIFIED GADDY TECHNIQUE

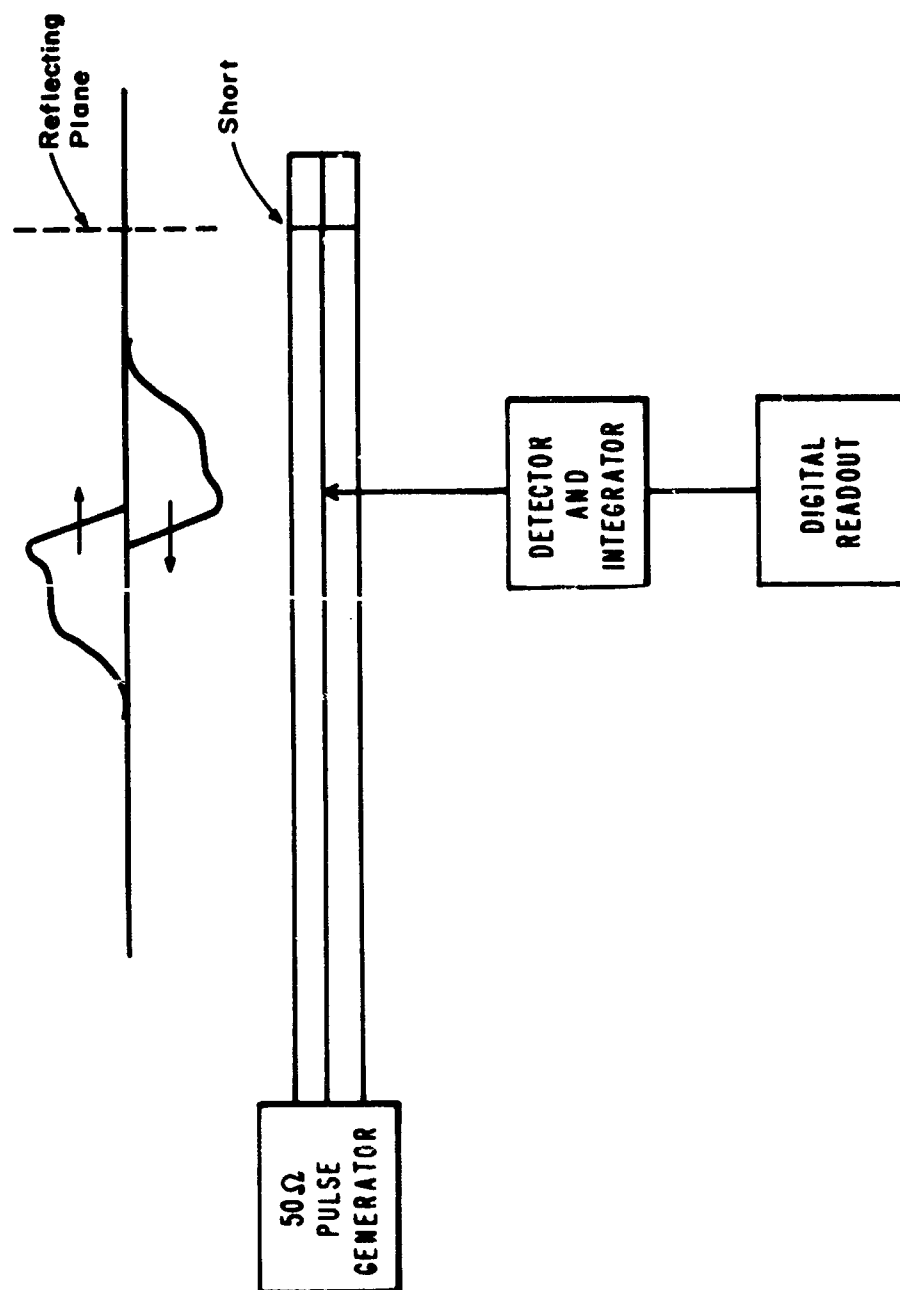


Figure 10

SECTION DRAWING OF PROBE IN LINE

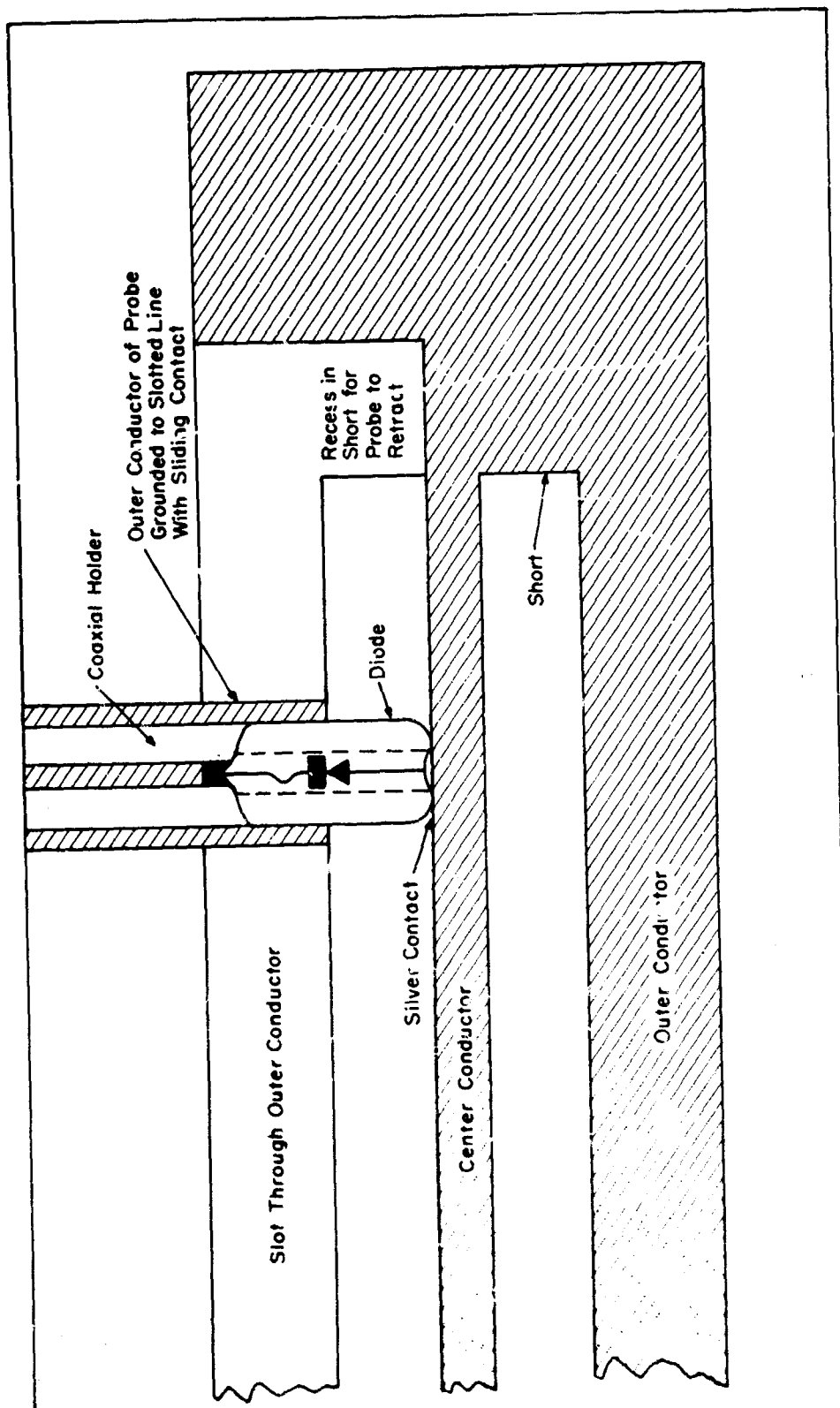


Figure 11

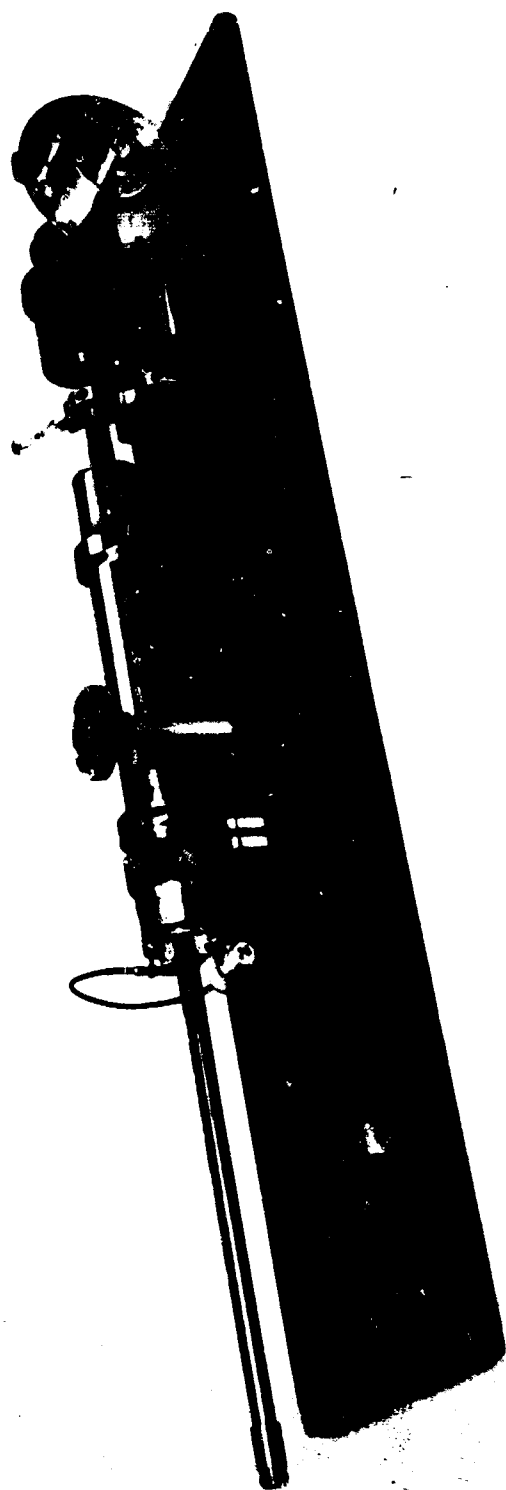


Fig. 12 Photograph of modified Gaddy equipment

The first phase of the computer analysis of the Gaddy technique is finished. A program has been developed that can generate data as if it were being produced by the Gaddy analyzer. This is necessary because the actual experimental measurement is very time consuming and also, measurement errors tended to hide the desired patterns in the data. The computer will accept a known pulse shape and generate data conveniently and economically. In this way many more pulse shapes can be examined.

A second program was developed that would accept this data and regenerate the original pulse. This is not simply the reverse of the previous program, because the process is not reversible as we have mentioned. For simple pulses the program makes a first approximation to the pulse. The computer generates data as if this approximate pulse were being analyzed in a Gaddy experiment. It then compares this approximate pulse data to the original data and corrects the pulse until it generates data that matches the original data. There are many pulse shapes that can generate the same data and the first approximation must be closer to the true pulse than to any of these degenerate pulse shapes. For simple pulse shapes the internally generated first approximation is sufficient. However, as the shape becomes more complex, there is provision for introducing this information into the program. For example, in standards work, the shape of the standard pulse will be at least approximately known by considering the design of the pulse generator. This information can be used as a first approximation and thus eliminate the ambiguities which might otherwise develop.

This second program needs to be evaluated for complicated wave shapes, to determine how close the first approximation has to be to avoid producing degenerate pulses. Each detector requires a different program to evaluate the data and introduces certain theoretical ambiguities into it's data. A scheme for combining these data has not been completed.

REFERENCES

1. Nahman, N. S. (June 1967), The measurement of baseband pulse rise-times of less than 10^{-9} seconds, Proc. IEEE, Vol. 55, No. 6, 855-864.
2. Wigington, R. L. and N. S. Nahman (Feb. 1957), Transient analysis of coaxial cables considering skin effect, Proc. IRE, Vol. 45-2, 166-174.
3. Nahman, N. S. (June 1962), A discussion on the transient analysis of coaxial cables considering high-frequency losses, IRE Trans. Ckt Theory, 144-152.
4. Allen, R. J. and N. S. Nahman (Oct. 1964), Analysis and performance of superconductive coaxial transmission lines, Proc. IEEE, Vol. 52-10, 1147-1154.
5. Hickey, B. (Feb. 1967), The role of the RF connector, Microwave Jour., 69.
6. Gilmore, J. F. (Aug. 1966), TE_{11} -mode resonances in precision coaxial connectors, General Radio Experimenter, Vol. 40-8, 10-13.
7. Reference Data for Radio Engineers (1956), ITT Corp., 4th Ed. 143, 646, 648.
8. Lee, G. M. (March 1946), A three-beam oscillograph for recording frequencies up to 10,000 megacycles, Proc. IRE, 121-127.
9. Bartenev, L. S., et al (July 1962), Ultra high speed pulse oscillograph, Instrumental Experiments & Techniques, No. 6, 1120-1123.
10. Brangaccio, D. J., et al (March 1958), Broadband oscilloscope tube, Bell System Tech. Jour., 447-460.
11. Germeshausen, K. J., et al (April 1957), A high-sensibility cathode-ray tube for millimicrosecond transients, IRE Trans. Electron Devices, 152-158.

12. Niklas, W. F. and J. Wimpffen (Nov. 1958), Oscilloscope tube with traveling wave deflection system and large field of view, Jour, Brit., IRE, 653-660.
13. Smith, S. T., et al (March 1952), Cathode-ray tube for recording high-speed transients, Proc. IRE, 297-302.
14. Coaxial deflection CRT has 3-Gc bandwidth, Microwaves (Feb 1963), 28-29.
15. Haines, M. E. and M. W. Jervis (Feb. 1957), The design and performance of a new experimental single-transient oscillograph with very high writing speed, Proc. IEE, Vol. 104, Pt. B, 385-392.
16. Haines, M. E. and M. W. Jervis (Feb. 1957), The ultimate performance of the single-trace high speed oscillograph, Proc. IEE, Vol. 104, Pt. B, 379-384.
17. Honey, R. C. (July 1954), A traveling-wave electron deflection system, IRE Trans. Microwave Theory & Tech., Vol. MTT-2, 29.
18. Pierce, J. R. (Nov. 1949), Traveling wave oscilloscope, Electronics, 97-99.
19. Owaki, K., et al (Oct. 1950), The traveling-wave cathode-ray tube, Proc. IRE, 1172-1180.
20. Whinnery, J. R. and H. W. Jamieson (Feb. 1944), Equivalent circuits for discontinuities in transmission lines, Proc. IRE, 98-114.
21. Lewis, I. A. D. and F. H. Wells (1959), Millimicrosecond pulse techniques, McGraw-Hill, 2nd Edition, Chapter 6.
22. Stonebraker, D. M., Analysis and design of an oscilloscope deflection systems with a calculable transfer function, unpublished.
23. Time domain reflectometry, H-P Appl. Note 62, (1964).
24. Cable testing with time domain reflectometry, H-P Appl. Note 67, (1965).

25. Poulter, H. (1965), Mechanical scaling enhances time domain reflectometry use, WESCON Record.
26. Hewlett-Packard Jour., (Oct. 1966).
27. Millman, Jacob and Herbert Taub, Pulse and digital circuits, McGraw-Hill Book Co., Inc., New York, N. Y., 41.
28. Lewis, I. A. D. and F. H. Wells, Millimicrosecond pulse techniques, Pergamon Press, New York, N. Y., 7.
29. Gaddy, Oscar (Dec. 1960), A simple method of measuring fractional millimicrosecond pulse characteristics, IRE Trans. on Instr. and Meas.
30. Ondrejka, A. R. and P. A. Hudson (Jan.-Mar. 1966), Measurement standards for low and medium peak pulse voltages, J. of Res., NBS, C. Engineering and Instrumentation, Vol. 70C, No. 1.
31. Honnold, G. H. and N. S. Nahman (June-Sept. 1964), On the applicability of the comparison method for picosecond pulse instrumentation, IEEE Trans. on Instr. and Meas.

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13. ABSTRACT This report presents the results of an investigation into various methods for measurement of the rise time of very fast pulses. The methods pursued under the study were: (1) the investigation of various types of coaxial reflection structures for use in a real-time oscilloscope, (2) characterization of the response of sampling oscilloscopes in the frequency domain and calculation of the response in the time domain and (3) the determination of pulse shape by the Gaddy autocorrelation technique. The techniques can be used to characterize the voltage waveform $V(t)$ of fast pulse systems such as impulse generators, time domain reflectometers and some digital and radar systems.			

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